Muon Beams for Future Experiments

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Capabilities Frontier Workshop

BNL April 2013

Disclaimer

- This is an overview and way too simplistic
- I will discuss this as an experimenter
- So therefore everything will not be even close to exactly right and all the definitions and boundaries are blurry.

Physics Goals

- What Experiments Do We Want To Do?
  - primarily charged lepton flavor violation (CLFV), muons changing into electrons without neutrino emission $\mu^+ \to e^+\gamma$ and $\mu^+ \to e^+e^+e^-$

    $\mu^+e^- \to \mu^-e^+$ $\quad$ $\mu^-N \to e^-N$ and $\mu^-N \to e^+N(Z-2)$
  - there are other things to measure but this is the killer app (IMO)
- What Is Our Goal?

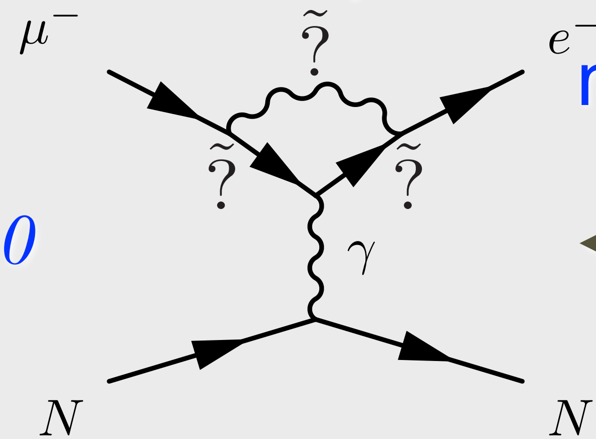
"If you can measure something an order of magnitude better, you should do it" – Jim Cronin, who did some good experiments at BNL

“Model-Independent” Form

$$\mathcal{L}_{\mathrm{CLFV}} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma_\mu u_L + \bar{d}_L\gamma_\mu d_L)$$

“Loops”

$\kappa = 0$



Supersymmetry and Heavy Neutrinos

Contributes to μ→eγ

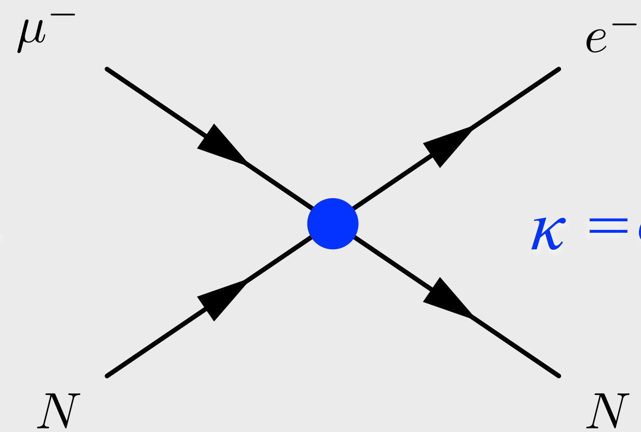
(just imagine the photon is real)

mass scale Λ

κ

$\longleftrightarrow$

“Contact Terms”



$\kappa = \infty$

New Particles at High Mass Scale (leptoquarks, heavy Z,...)

Does not produce μ→eγ

Quantitative Comparison?

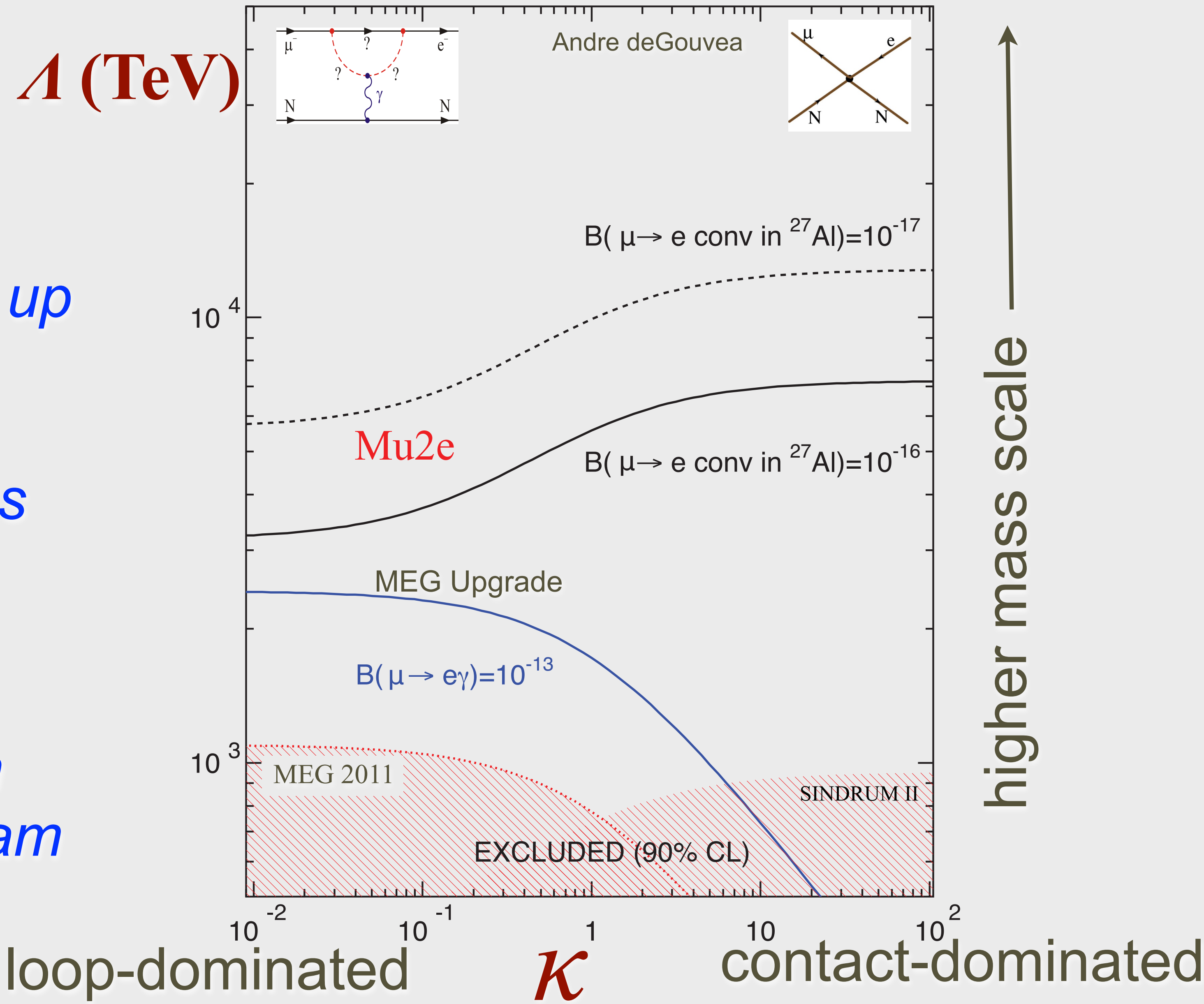
μe Conversion and μ→eγ

CLFV:

probes masses up to 10^4 TeV/c^2

next generations are discovery experiments

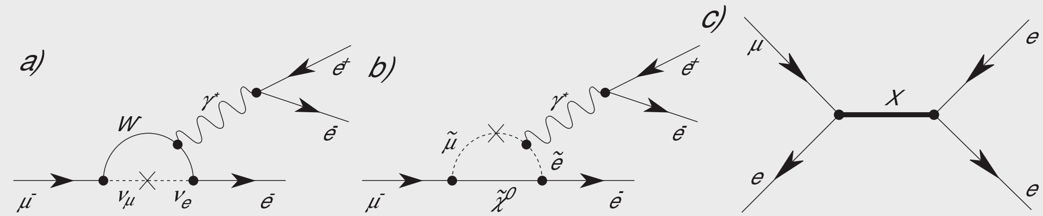
new beams can build rich program



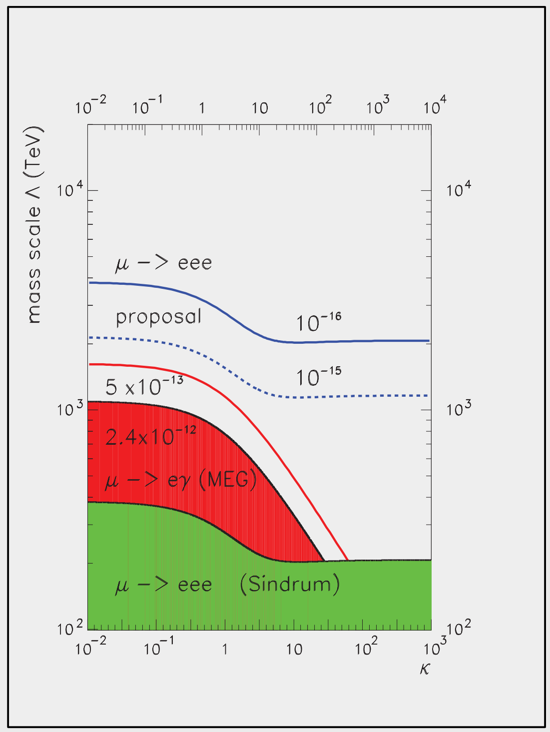
$\mu \to 3e$

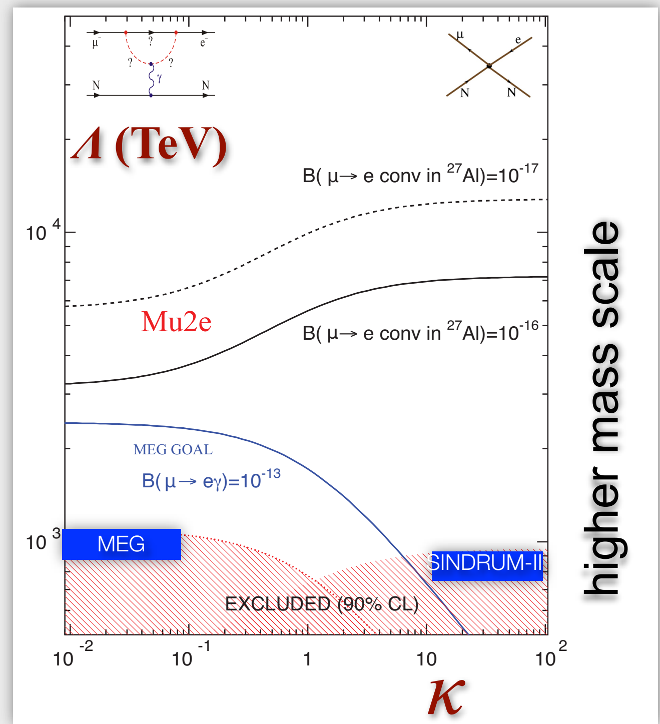
Hisano

$$L_{\text{eff}} = \frac{m_\mu}{\Lambda^2}\overline{e}(\sigma^{\mu\upsilon}F^{\mu\nu})\mu + \frac{1}{\Lambda_F^2}\overline{e}\Gamma_A e\,\overline{e}\Gamma_A\mu + \frac{1}{\Lambda_F'^2}\overline{q}\Gamma_A q\,\overline{e}\Gamma_A\mu$$

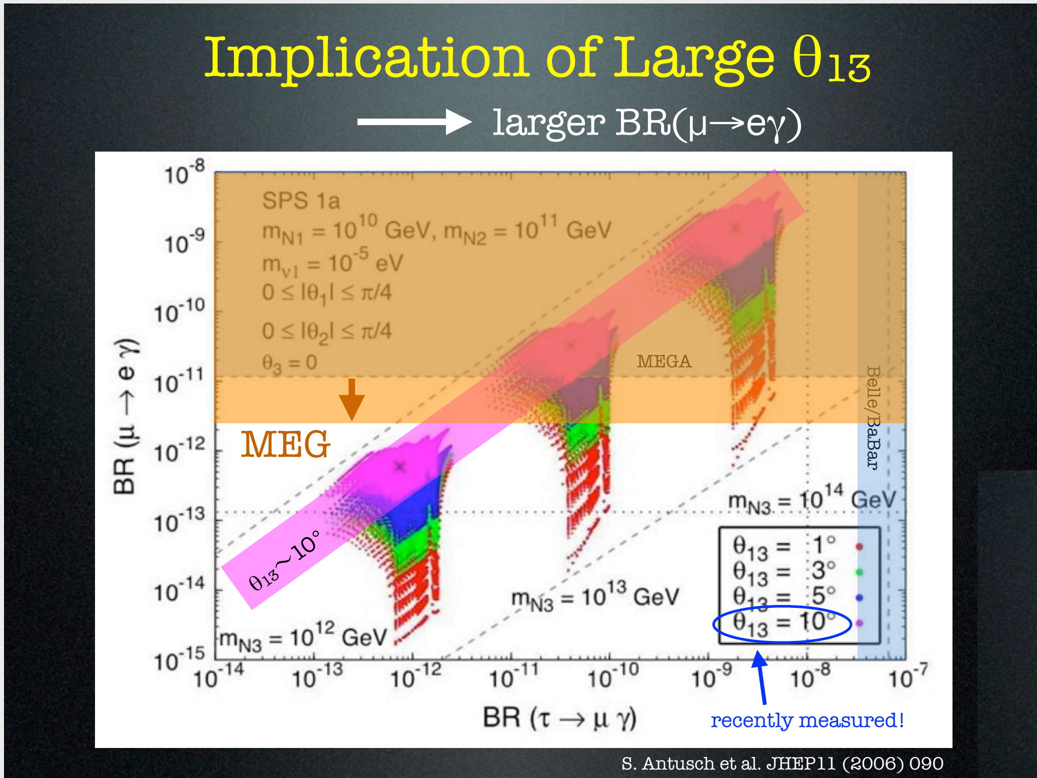


- "Sister" process to $\tau \to 3l$
- The meaning of κ is not the same since the underlying diagrams are different, but still indicative
- *reaching "ultimate" sensitivity, limited by radiative background, may require surface muon beams to get sufficient statistics*



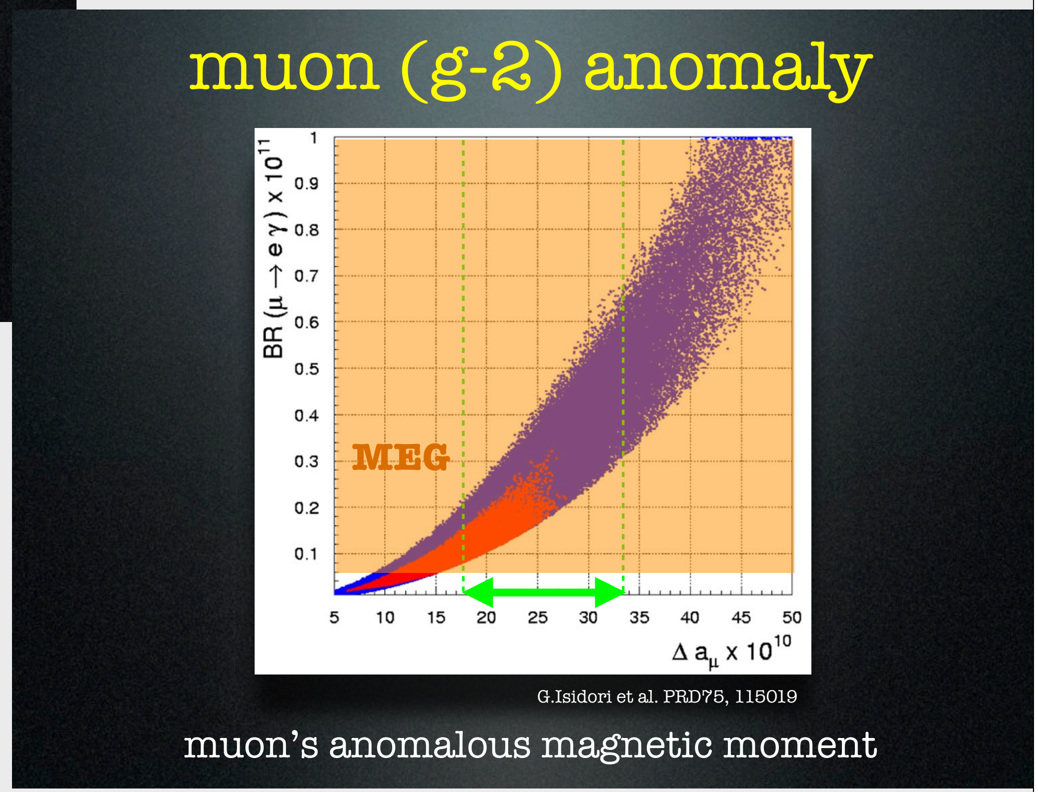


Specific Examples



Combining MEG at PSI

with $\tau \to \mu\gamma$



with BNL821 g-2

Surface Muon Beams

"Arizona Beam"

A. Pifer et al., NIM 135, 39.

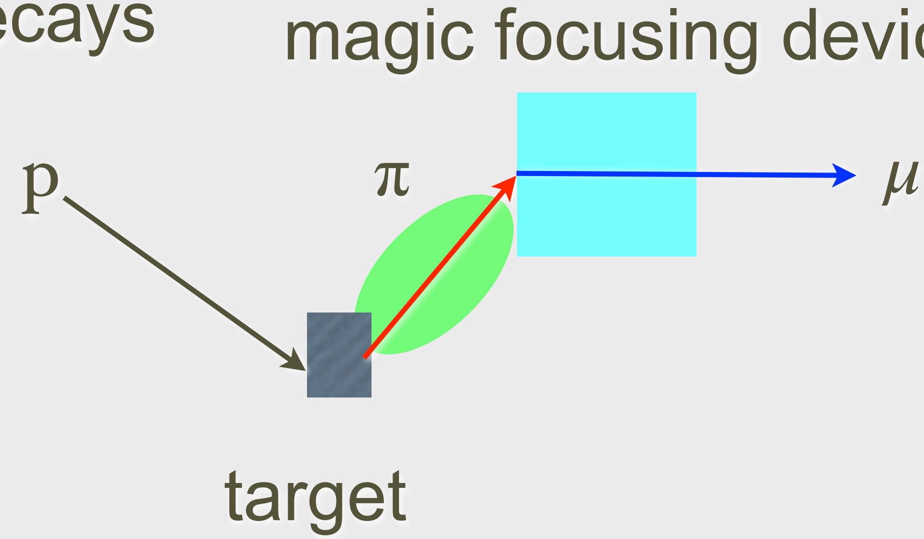
$$p \longrightarrow \pi \longrightarrow \mu$$

- Pions range out and decay close to the surface of a target and yield muons at 29.8 MeV/c (MEG may go slightly sub-surface; see below eqn.)
  - Source is very well defined
  - Polarization (pion stopped) near 100%
  - μ^+ only since π^- would be captured on nuclei
    - positron contamination

$$R_\mu \sim p^{3.5} \sqrt{\left(3.5 \frac{\Delta p}{p}\right)^2 + \left(\Delta R_{\text{straggling}}\right)^2}$$

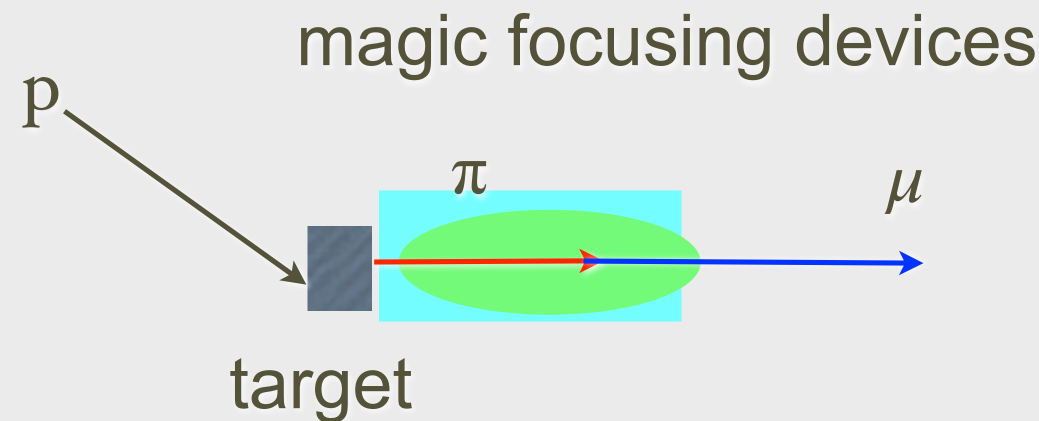
Cloud Muon Beams

"surface beam" but pion decays outside target



- Large momentum range
- Source bigger than production target
- Contamination of both charges of pions and electrons
- Low Polarization

Decay Muon Beams



- Source much bigger than production target
- Polarization high; by using pion lifetime, contamination low
- Very flexible
  - neutrino horn beams
  - many DIS experiments

“cloud beam” but select pion momentum

Experiments

- Reorder the experiments into beam type:
  - two stopped muon processes: *stopped→+*

    $$\mu^+ \to e^+\gamma \text{ and } \mu^+ \to e^+e^+e^-$$

  - two captured muon processes in clouds *captured→-*

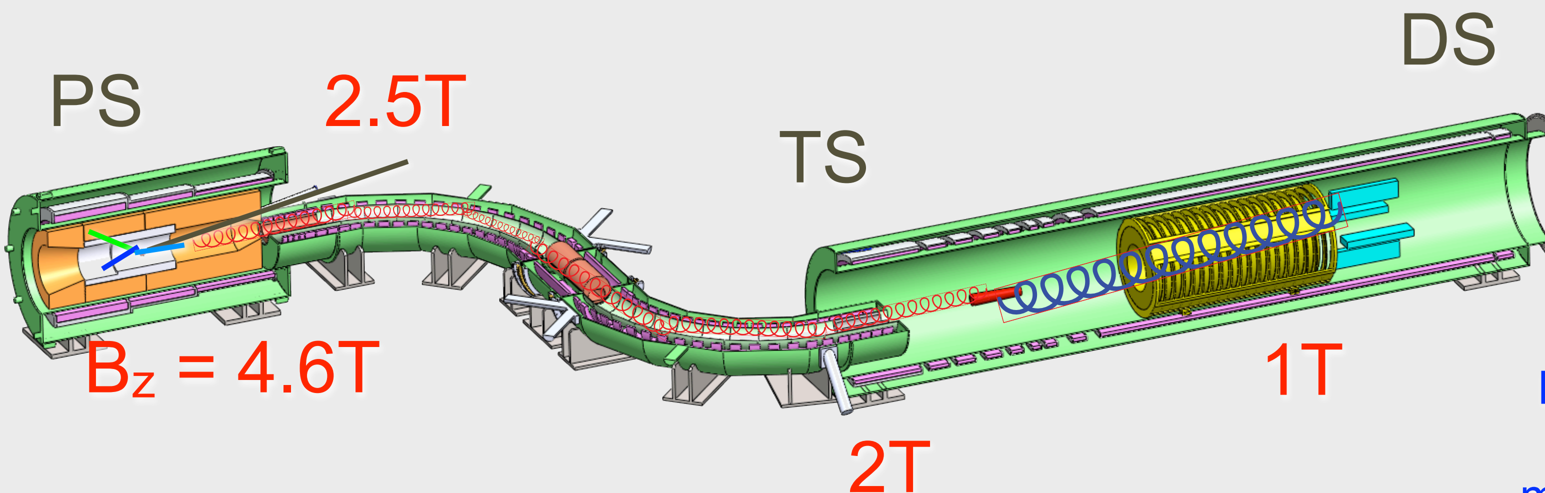
    $$\mu^- N \to e^- N \text{ and } \mu^- N \to e^+ N(Z-2)$$

  - muonium-antimuonium oscillation and muonium HFS from cloud beam

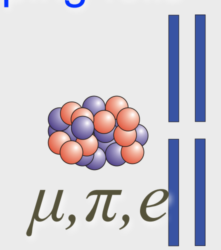
    $$\mu^+ e^- \to \mu^- e^+$$

Mu2e Muon Beam: Three Solenoids and Gradient

4.6T ⟶ B-field gradient ⟶ 1T



Muon Momentum ~ 50 MeV/c: muons range out in stopping foils



- Target protons at 8 GeV inside superconducting solenoid
- Capture muons and guide through S-shaped region to Al stopping target
- Gradient fields used to collect and transport muons

To Pulse or Not To Pulse?

- Pulses:
  - width of pulse
  - time between pulses
  - shape of pulse
  - “extinction”: suppress beam between pulses
- In general (but NOT a fine line)
  - stopped muon experiments want as DC a beam as possible to keep instantaneous rates low
  - capture muon experiments want varying pulse width and separation depending on lifetime in capture atom

What Exists?

http://arxiv.org/pdf/1301.7225v2.pdf

Laboratory / Beam line	Energy / Power	Present Surface μ^+ rate (Hz)	Future estimated μ^+/μ^- rate (Hz)
PSI (CH)	(590 MeV, 1.3 MW, DC)		
LEMS	″	$4 \cdot 10^8$	
πE 5	″	$1.6 \cdot 10^8$	
HiMB	(590 MeV, 1 MW, DC)		$4 \cdot 10^{10}(\mu^+)$
J-PARC (JP)	(3 GeV, 1 MW, Pulsed) currently 210 KW		
MUSE D-line	″	$3 \cdot 10^7$	
MUSE U-line	″		$4 \cdot 10^8(\mu^+)$ (2012)
COMET	(8 GeV, 56 kW, Pulsed)		$10^{11}(\mu^-)$ (2019/20)
PRIME /PRISM	(8 GeV, 300 kW, Pulsed)		$10^{11-12}(\mu^-)$ (> 2020)
FNAL (USA)			
Mu2e	(8 GeV, 25 kW, Pulsed)		$5 \cdot 10^{10}(\mu^-)$ (2019/20)
Project X Mu2e	(3 GeV, 750 kW, Pulsed)		$2 \cdot 10^{12}(\mu^-)$ (> 2022)
TRIUMF (CA)	(500 MeV, 75 kW, DC)		
M20	″	$2 \cdot 10^6$	
KEK (JP)	(500 MeV, 2.5 kW, Pulsed)		
Dai Omega	″	$4 \cdot 10^5$	
RAL -ISIS (UK)	(800 MeV, 160 kW, Pulsed)		
RIKEN-RAL		$1.5 \cdot 10^6$	
RCNP Osaka Univ. (JP)	(400 MeV, 400 W, Pulsed)		
MUSIC	currently max 4W		$10^8(\mu^+)$ (2012) means> 10^{11} per MW
DUBNA (RU)	(660 MeV, 1.65 kW, Pulsed)		
Phasatron Ch:I-III		$3 \cdot 10^4$	

Examine Some Experiments

closely related experimentally to $\mu^+ \to e^+e^+e^-$

- MEG: $\mu^+ \to e^+\gamma$

PSI: ~51 MHz , 300 psec wide

  - need to stop muons and let them decay
  - signal is back-to-back photon and electron

why well-defined stop

why DC

$$\mathcal{B} \quad \propto \quad (\frac{R_\mu}{D})(\Delta t_{e\gamma})\frac{\Delta E_e}{m_\mu/2}\left(\frac{\Delta E_\gamma}{15m_\mu/2}\right)^2\left(\frac{\Delta\theta_{e\gamma}}{2}\right)^2$$

  - R/D term is rate over duty cycle: want DC beam as constant as possible over macroscopic time
  - $\Delta\theta_{e\gamma}$ is vertexing: surface muons, well-defined stop location

http://arxiv.org/pdf/1301.7225v2.pdf

What Do They Have Now?

should regard this as a challenge

A. The MEG beam line and muon target

A schematic of the MEG beam line and the $\pi E5$ channel is show in Fig. 11. Driven by the world's most intense DC proton machines at the Paul Scherrer Institut's high-intensity proton accelerator complex HIPA, it constitutes the intensity frontier in continuous muon beams around the world (c.f. Table II) and as such, is capable of delivering more than 10^8 μ^+/s at 28 MeV$/c$ to the MEG experiment. The surface muon beam has distinct advantages over a conventional 2-step pion decay-channel.

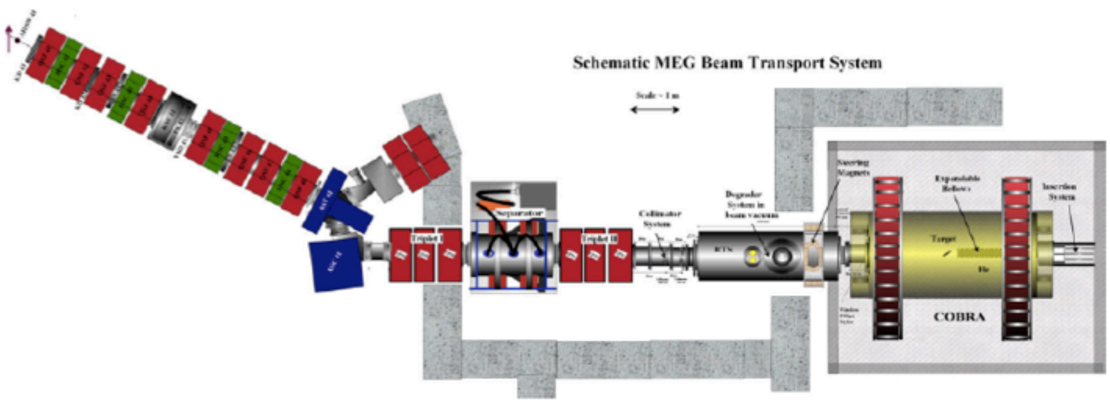


FIG. 11: (Left-part) shows the $\pi E5$ channel, connecting the production target E to the $\pi E5$ area. The MEG beam line starts from the extraction element Triplet I exiting the wall, followed by a Wien-filter, Triplet II and a collimator system, used to eliminate the beam contamination. The final range adjustment and focusing is performed by a superconducting solenoid BTS, before the muons are stopped in an ultra-thin target placed at the centre of the COBRA positron spectrometer.

What Would We do Next?

- How Do We Progress?
  - just-approved MEG upgrade is x10 from existing: beyond that?
- This is pure speculation and my personal opinion:
  - convert the photon and use tracking
  - limits from tracking, not calorimetry
- But you lose a lot of rate, since converter must be thin or experiment will suffer from multiple scattering

Rough Guesses

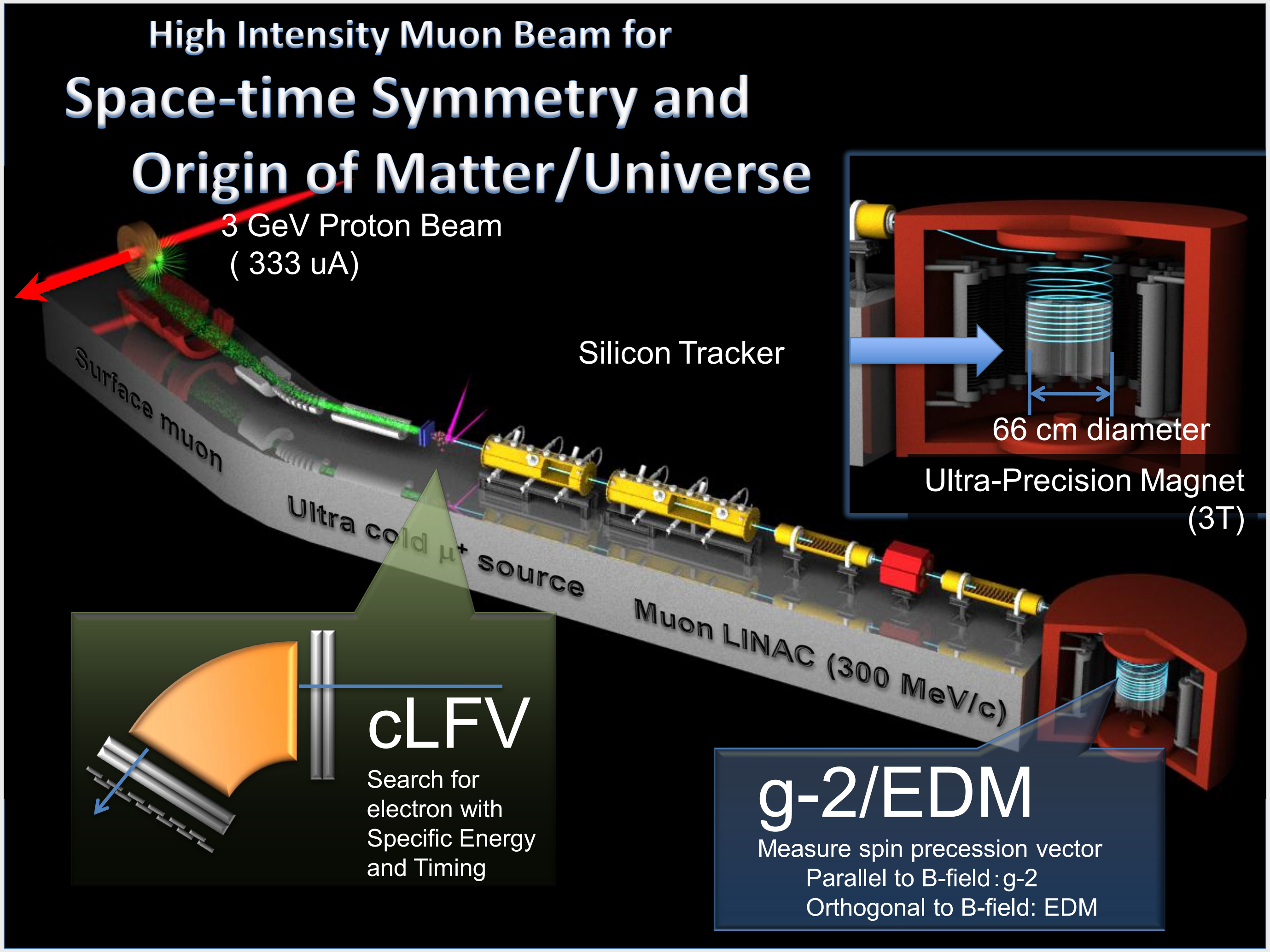
- 10^{11} stopped muons/sec
- surface or sub-surface positive muon beam
    - recall $R \sim p^{3.5}$ so small drop in momentum is big change in range, helps with vertex
- as continuous as possible (10-20 nsec rep rate probably fine)
- proton energy? don't care for MEG but matters for Mu2e (pbars) -- so experiment-dependent

Muon Spin Rotation

- See https://indico.fnal.gov/conferenceDisplay.py?confId=6025
- Applications in
  - materials science
  - condensed matter
  - chemistry
- don't have time or knowledge to discuss

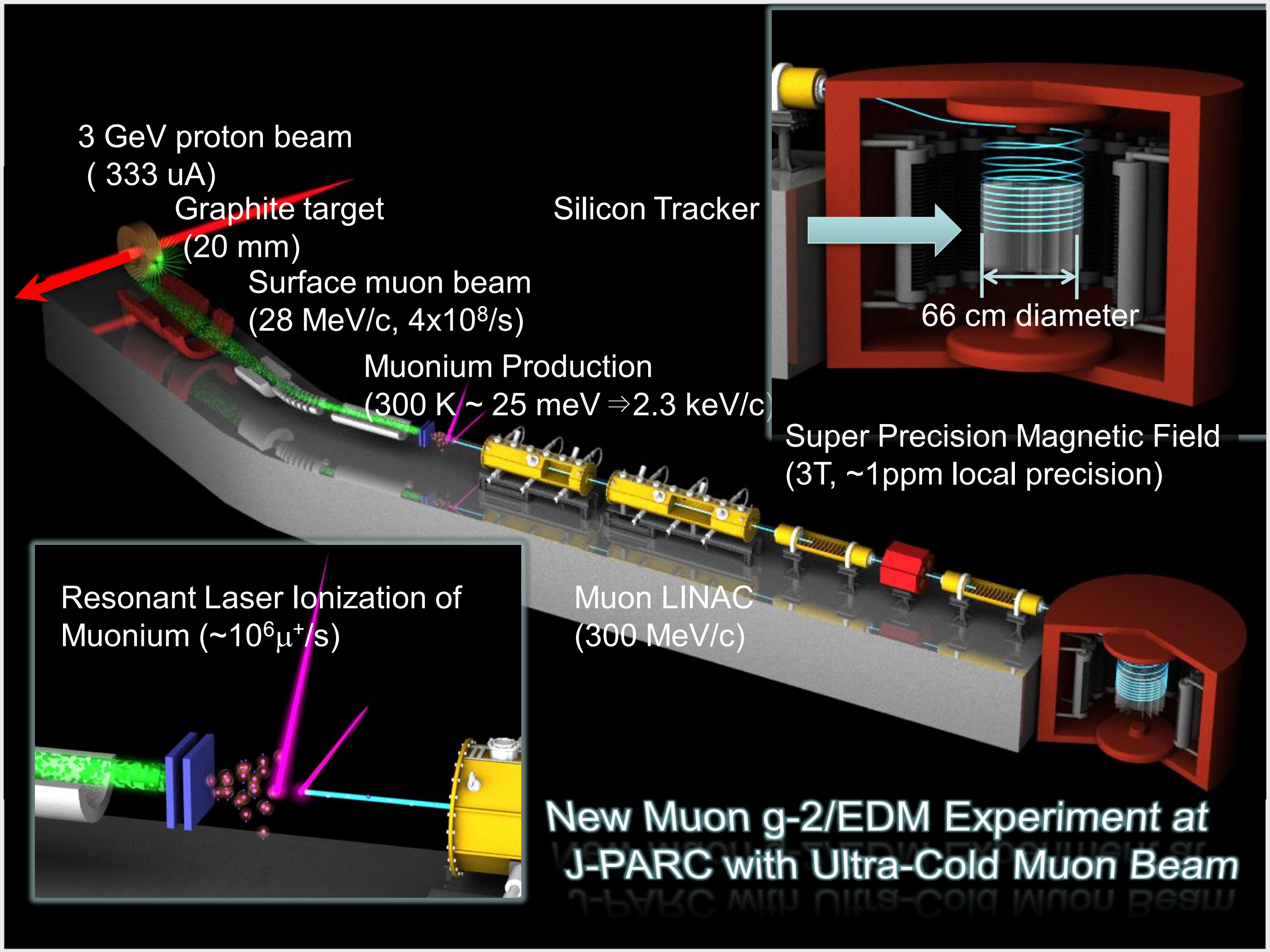
Japanese Plans

- different g-2 technique
  - “cold g-2”, not magic momentum
- CLFV: DeeMe, separate from COMET and x100 less sensitive
- and EDMs



Status: Much to Work On!

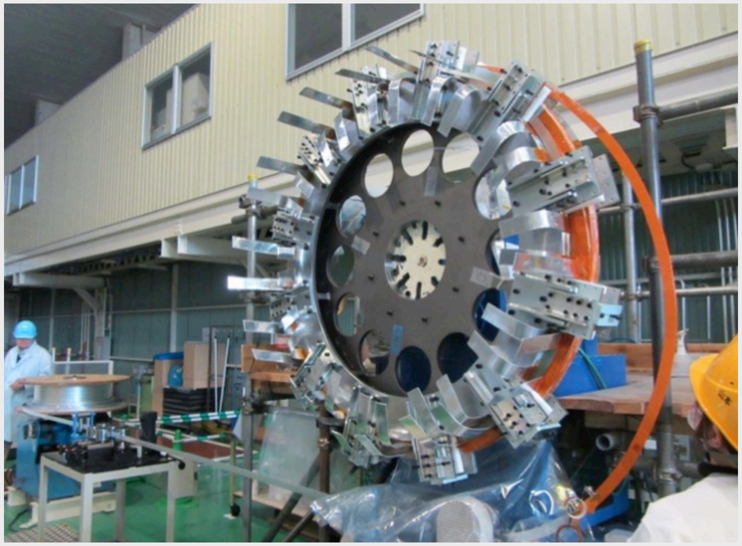
- yield of muonium too low to be useful; precise numbers hard to get
- surface muon rate way too low for competitive next-gen expt in CLFV



U.S losing in pretty picture department

Mu2e: Status

- US Mu2e at CD1 planning for CD2 winter 2013
- Data ~2020
- Prototyping underway
  - 3 km of test cable in fall 2013



Next-Gen Mu2e

- Will Current Method Work?
    - depends on a lot

probably ~ x10 with some improvements/ experience

need big changes

Limits: non-beam

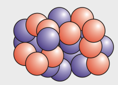
- Cosmic Ray Backgrounds
  - make it deeper, just money
- Decay-in-Orbit Spectrum
  - intrinsic physics background, overcome with resolution and statistics

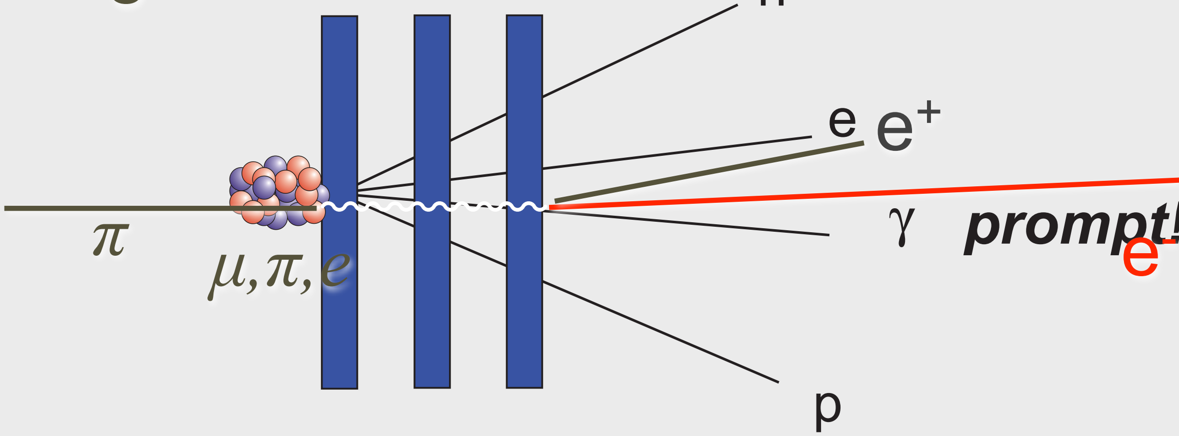
Beam Related Limits

- Must understand one key background: radiative pion capture (RPC)
- No time to discuss details, but antiprotons also make RPC if they arrive at experiment
  - 8 GeV KE booster makes pbars
  - 3 GeV below threshold; probably best
  - 1 GeV probably fine

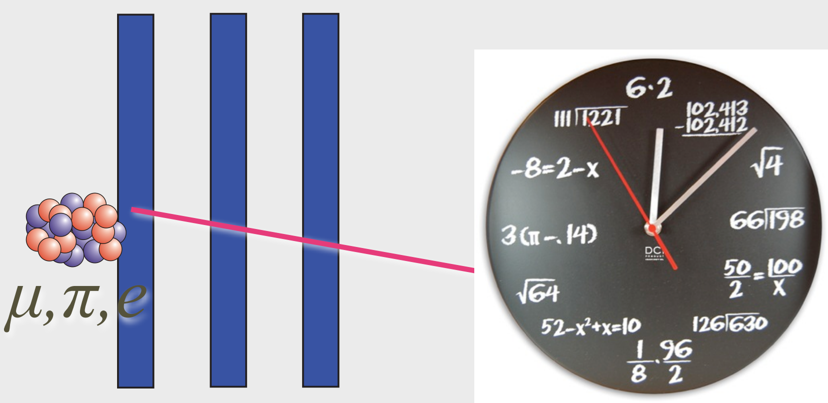
Prompt backgrounds and Pulsed Beam

target foils: muon converts here


= muons, electrons, pions



pulsed beam lets us wait until after prompt backgrounds disappear and rate lowered



delayed 105 MeV electron

Radiative Pion Capture:

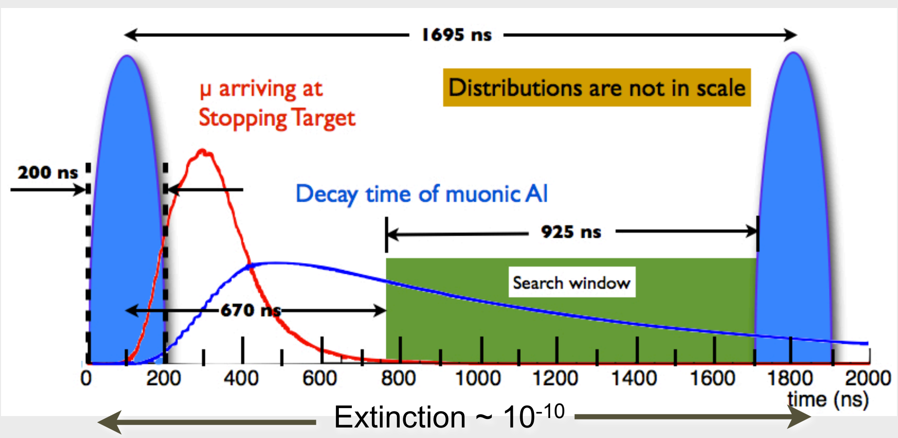
$\pi N \rightarrow \gamma N$

$\gamma \rightarrow e^+ e^-$ *in foils*

Pulsed Beam Structure

- Tied to prompt rate and machine: FNAL "perfect"
- Want pulse duration << τ_μ^{Al} , pulse separation ≈ τ_μ^{Al}
  - FNAL Debuncher has circumference 1.7µsec , ~x2 τ_μ^{Al}
- Extinction between pulses < 10^{-10} needed

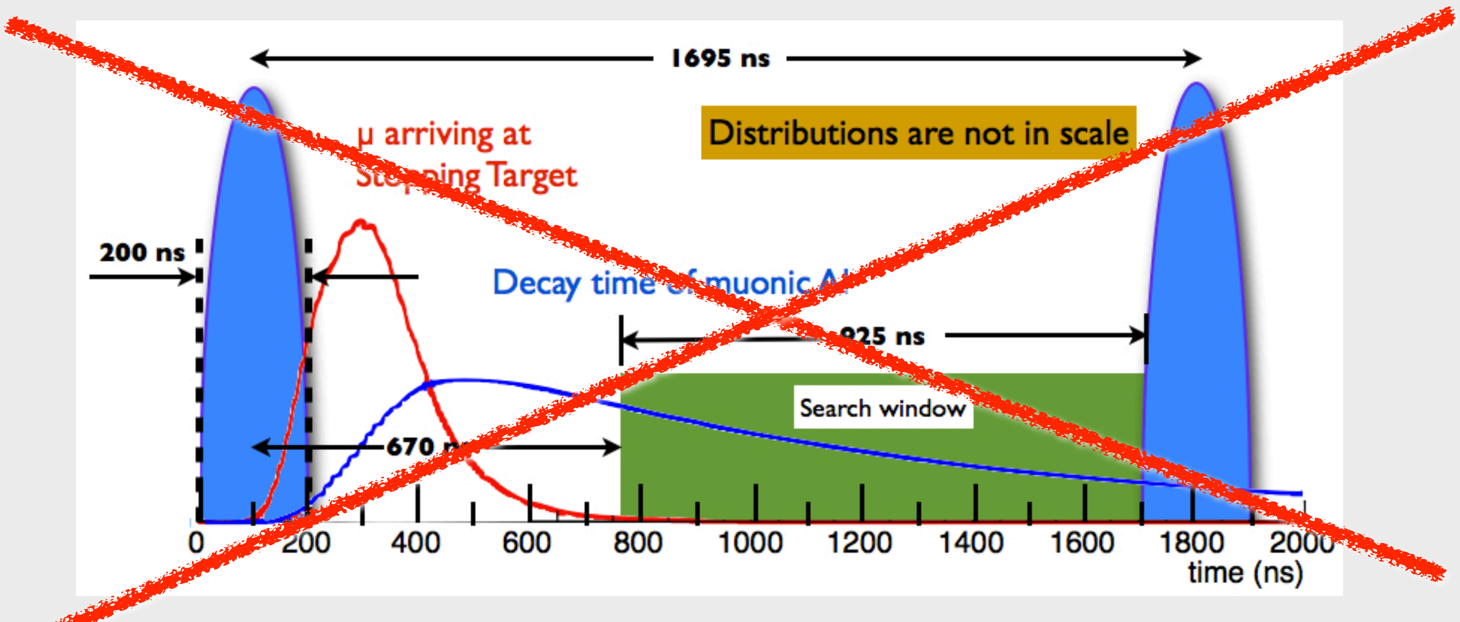
  = # protons out of pulse/# protons in pulse



- 10^{-10} based on simulation of prompt backgrounds and beamline

What Has to Change?

- If we see a signal, need to go to higher *Z*
- Lifetime of the captured muon decreases with higher *Z*
- For Au, lifetime = 72.6 nsec: *inside beam pulse!*



Different Muon Beams

http://www.sciencedirect.com/science/article/pii/S0920563211005330

- Would like to let all pions decay and then extract muons: no background, no extinction...
- Would be even better if muons nearly monochromatic: tightly controlled stopping location
  - PRISM/PRIME idea at J-PARC
    - FFAG kicker not on mass shell yet
  - Other ideas?
    - Do they lead to neutrino factory/muon collider?

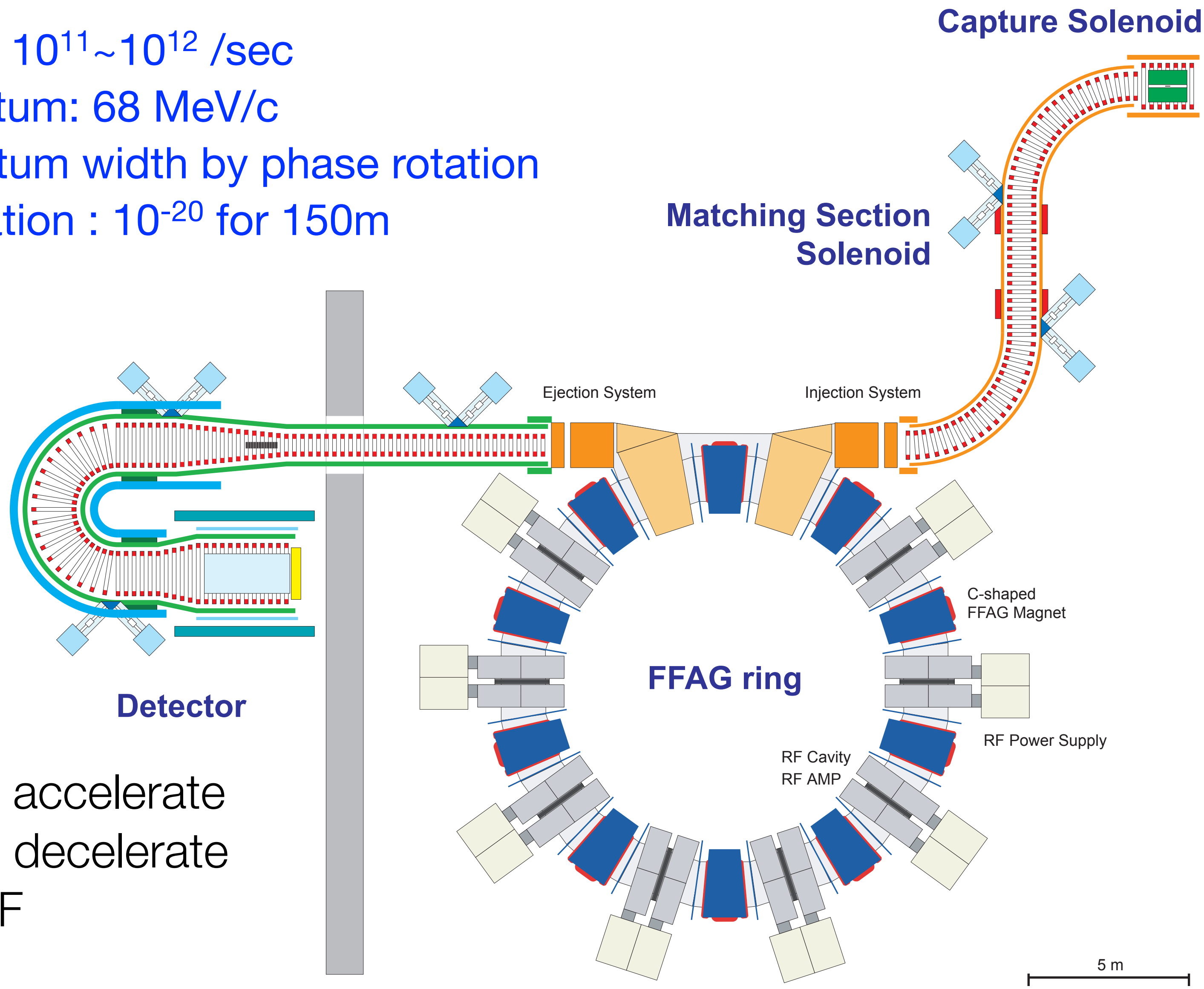
PRISM

$$B(\mu^- + Ti \rightarrow e^- + Ti) < 10^{-18}$$

- muon intensity: 10^{11}~10^{12} /sec
- central momentum: 68 MeV/c
- narrow momentum width by phase rotation
- pion contamination : 10^{-20} for 150m

Table 1
Accelerator Parameters of the PRISM system.

Proton Beam	
Beam power	0.75 - 2 MW
Beam Kinetic Energy	2-8 GeV
Bunch length at the target	15 ns total
Repetition rate	1 KHz
Target & π/μ transport	
Target Type	Solid
Capture Elements	Solenoid 4-10 T
Transport System	solenoidal channel & FFAG transport line
Beam Polarity	Negative
PRISM ring	
Machine type	FFAG
Momentum Acceptance	±20 %
Reference muon momentum	40-50 MeV/c
Acceptance (H/V)	(3.8/0.57) πcm rad
Harmonic number	1
RF Voltage per turn	5.5 MV
RF frequency	3-6 MHz
Injection/extraction type	single turn
Extraction Kicker Rise Time	50-60 ns
Repetition Rate	1 KHz
Initial momentum spread	±20 %
Final momentum spread	±2%
No. of turns	6
Synchrotron oscillations	$\frac{1}{4}$ or $\frac{3}{4}$

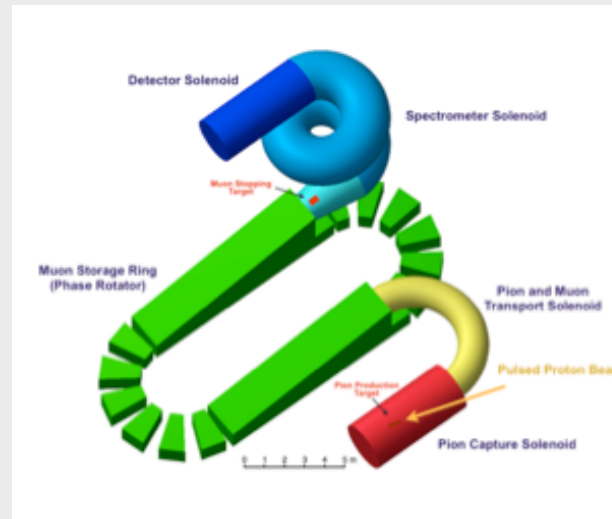


Phase rotation = accelerate slow muons and decelerate fast muons by RF

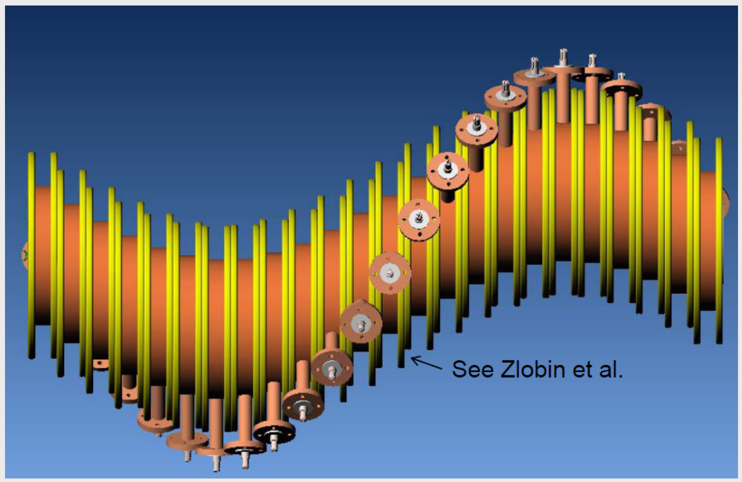
Other Ideas

- Racetrack FFAG

  J. B. Lagrange et al,Straight Section in Scaling FFAG Accelerator,Proc. PAC09, FRF5PFP002, Vancouver, Canada, 2009

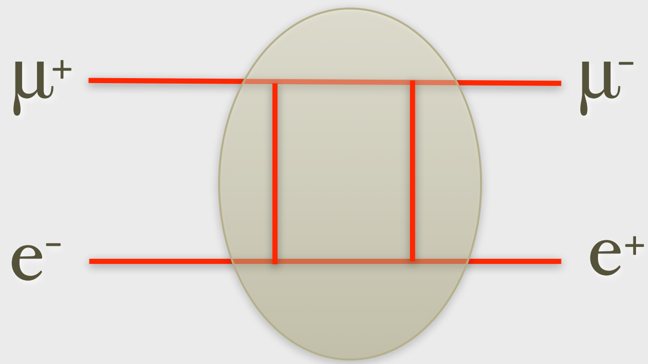


- HCC



- Other?
  - http://projectx-docdb.fnal.gov/cgi-bin/ShowDocument?docid=996

Muonium/AntiMuonium



V-A new physics: coupling

$$G_{\mathrm{Mu\overline{Mu}}}$$

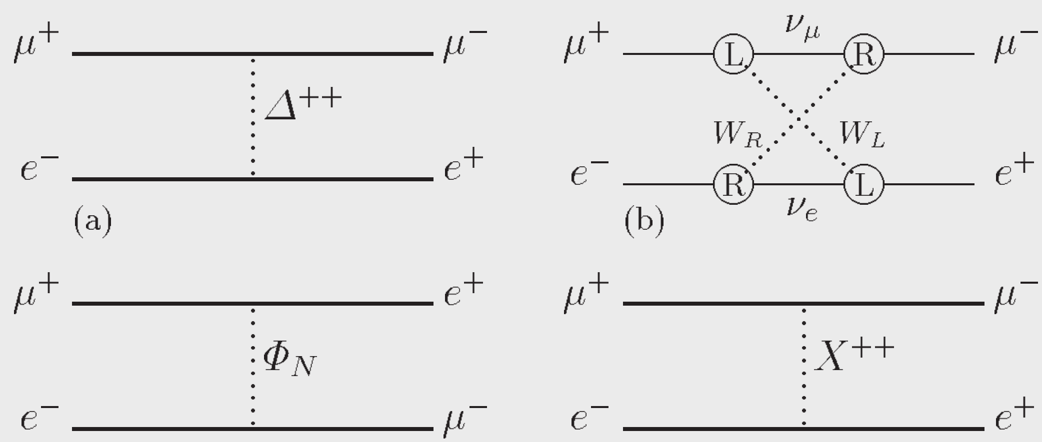
- World's best limit from PSI : (Willmann, L., Jungmann, K. et al.(1999), Phys. Rev. Lett. 82, 49)

$$\Delta L = 2$$

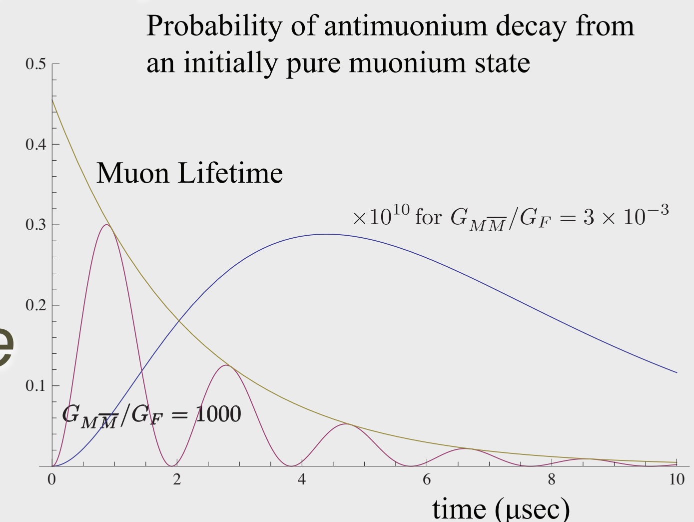
$$\mathrm{G}_{\mathrm{Mu\overline{Mu}}} < 3 \times 10^{-3}\mathrm{G_F}\ (\text{Probability of spon. transition } < 8.2 \times 10^{-11})$$

- Wide variety of Beyond Standard Model Physics
- Could be improved x100 with better resolution and pulsed beam, so ~ $10^{-5}G_F$

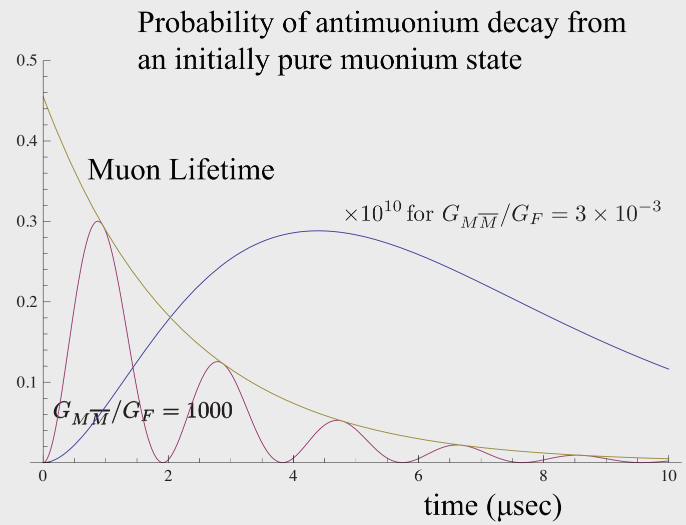
Muonium-Antimuonium



- Number of models
  - doubly charged Higgs, heavy Majorana neutrinos, ...
  - oscillates like $K^0 - \bar{K}^0$
  - *but damped by muon lifetime*



Time-Behavior



- Prepare muonium
- Look for positrons vs. time
  - positron left behind after negative muon decay at “1s” energy of 13.5 eV
- But there’s a muon decay background:
  - $\mu^+ \rightarrow e^+ e^- e^+ 2\nu$
  - sometimes the electron is background

So Pulse Beam to Suppress Muon Decay

- Wait enough muon lifetimes to suppress decays
- Want pulses (somewhat arbitrary) five muon lifetimes apart
- then the rest is the detector resolution
- should be able to do x100 better(from discussions with people who did last generation)
- muonium yield requirement not as stringent as cold g-2, should be manageable

Summary

- One accelerator? Multiple Accelerators?
    - that’s for you to decide
- Sociological Comment: in neutrino world, get a big advantage from multiple neutrino experiments at one site; similar constructive interference between g-2 and Mu2e
    - grad student/post-doc pipeline
    - easier to build a program
    - well-demonstrated at PSI

Conclusions: Beam Requirements

- Wide variety of beams required
  - pulse rates, muon energy, etc. vary
- Flexibility and Power are most important drivers

Physics Process	Continuous/Pulsed	Capture /Stopped	$\sim$ # Muons	Muon KE
$\mu \to 3e$	continuous	stopped	$\mathcal{O}(10^{18})$	surface
$\mu \to e\gamma$	continuous	stopped	$\mathcal{O}(10^{18})$	surface
$\mu^- N \to e^- N$	pulsed	capture	$\mathcal{O}(10^{23})$	≤ 50 MeV
$\mu^- N \to e^+ N(A, Z-2)$	pulsed	capture	$\mathcal{O}(10^{21})$	≤ 50 MeV
$\mu^+ e^- \to \mu^- e^+$	pulsed	stopped	$\mathcal{O}(10^{15})$	surface

these are very rough numbers